SPIN
Progress and Prospects

A Talk Presented at SPIN2000, October 30, 2000

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Abstract. I review the progress in fundamental spin physics over the past several years and the prospects for the future. The progress is striking and the prospects are excellent.

INTRODUCTION

I would like to thank the organizers for the honor of delivering the opening talk at this Millennial Conference on Spin in High Energy and Nuclear Physics. Much is new, more will be forthcoming soon. These are exciting times.

Like this conference, my talk will focus on spin in QCD. The organizers asked me to stress progress and prospects, which I will do. The prospects for remarkable advances in the near future – involving spin in one way or another – in electroweak unification and even in gravity compels me to mention those fields as well.

In his welcome to SPIN98 in Protvino, Charlie Prescott, began his talk by pointing out a striking geographical correlation between the historical march of successive spin conferences and the Earth's angular momentum [1]. Our location in Osaka once again displays the "Prescott Effect". I have updated the data in Fig. 1. Word has it that the 2002 conference will move to Brookhaven, once again confirming Prescott's Effect. The rule, of course, displays the remarkably international character of these conferences, which we all hope will continue forever. Parenthetically, as a theorist, I have to note the Anomaly that occurred in 1986–1988, when the conference counter-rotated from the USSR to the USA. Prescott appears to have fudged his data to downplay this intriguing Anomaly – it deserves further study.

Turning to more serious questions: The stuff of the world falls into two categories: (1) Gauge fields, which are bosons and are required by local symmetries of space-time. Gravitons follow from general covariance. W's, Z's, photons and gluons spring from local phase invariances. And (2) Matter, which is composed of spin-$^1/_2$ particles, quarks, and leptons that carry the quantum numbers of ungauged, global symmetries.

[1]) This work is supported in part by funds provided by the U.S. Department of Energy (D.O.E.) under cooperative research agreement #DF-FC02-94ER40818. MIT-CTP#3075

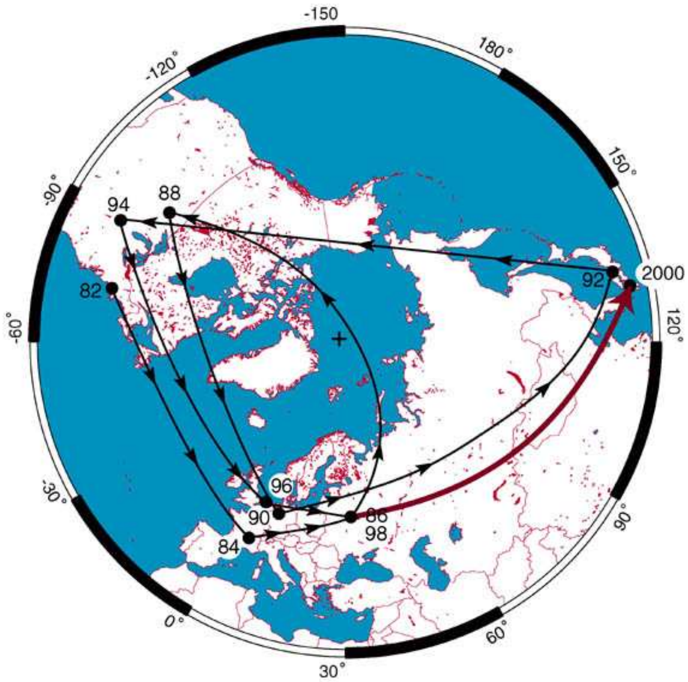

FIGURE 1. The Prescott Effect.

So far there are *no spinless elementary particles at all!* One can argue that this pattern follows in part from the constraints of renormalizability: Massive vector bosons unrelated to gauge symmetries should not appear in our low energy, renormalizable effective Lagrangian. Spinless particles might be propelled to Planck scale masses by quadratically divergent self energies. A couple of questions stand out: Why are there no spinless elementary particles? Why do only the fermions carry the ungauged, global quantum numbers. Why does matter exist at all, since the (Yang-Mills and Einstein) gauge theories are quite consistent and content without them?

Remarkably, we may be close to obtaining new experimental input into these profound questions.

- There is some evidence that a scalar Higgs boson awaits discovery at a mass around 115 GeV. Early indications at LEP will have to wait for FNAL or LHC for confirmation. Of course radiative corrections to the Standard Model now constrain the Higgs mass reasonably well. So unless Nature deals us a major surprise, the discovery of the first spinless elementary particle is imminent.

- A light Higgs suggests (but does not require) that supersymmetry is the natural extension of the Standard Model. If so, we can expect to discover two entirely new forms of matter required by supersymmetry. First, fermions without flavor associated with gauge symmetries – the "ino"s of SUSY like the gluino. Supersymmetric partners of the gauge bosons, they know nothing about the flavor symmetries of ordinary matter. Second, the scalar partners of quarks and leptons, which carry global flavor quantum numbers – the "sparticles" of SUSY – these would be the first bosons carrying the global symmetries which characterize matter.

There are other good reasons to believe in supersymmetry: partial resolution to the hierarchy problem, coupling constant unification, and dark matter candidates are most often mentioned. It is worth remembering, however, that SUSY introduces particles which are qualitatively different from those we have known up to now.

Over the next few years, *spin* will play a central role in testing and looking beyond the Standard Model and in exploring the unresolved mysteries of QCD. Two examples will illustrate the importance of spin in tests of the Standard Model:

- The muon's magnetic moment, $(g-2)_\mu \equiv 2a_\mu$ will be measured with nearly 20 times existing precision by the Brookhaven $g-2$ experiment. At this precision a_μ probes certain extensions of the Standard Model up to energies equivalent to LEP and the Tevatron, and is sensitive to SUSY and other novelties.
- Electric dipole moments (EDM's) fascinate both theorists and experimenters. They probe CP violation, one of the most poorly understood aspects of the Standard Model. If all CP-violation is encoded in the CKM matrix, EDM's are too small to measure. For this reason EDM's are an excellent place to look for CP-violation beyond the Standard Model. The problem of baryogenesis in the early Universe continues to suggest that other sources of CP-violation are waiting to be discovered.

Spin has recently proved itself a very powerful tool to probe the internal structure of hadrons in QCD. We have measured the quark spin contribution to the spin of the nucleon, but we do not understand it. In fact, we know more about the spin of the *graviton*, which has never been observed, than we do about the spin of the nucleon, which composes most of the luminous mass in the Universe. Several new results from the Hermes collaboration at DESY and the SAMPLE collaboration at Bates whet the appetite for future measurements of spin observables in QCD. I will review the outstanding issues in QCD spin physics in the latter 2/3 of this talk.

Finally, I cannot fail to mention the experimental and technical foundations on which our field rests. Spin physics would go nowhere without the extraordinary creativity and devotion of accelerators physicists, who have developed novel methods of accelerating, storing and colliding polarized particles and without experimentalists who have devised high density, high polarization targets, and polarimeters and detectors capable of incredible sensitivity. Were not for this remarkable effort, we theorists might as well do string theory.

BEYOND THE STANDARD MODEL

As an appetizer to QCD, which is the main course at this meeting, here is a quick survey of some issues in spin physics beyond the Standard Model.

The spin of the graviton

We know that the graviton has spin two. Standard tests of general relativity and the measured deceleration of the Hulse-Taylor pulsar assure us of this. Still, it would be nice to have direct observation of gravitational radiation and explicit confirmation

of its tensor nature. LIGO, the Laser Interferometry Gravitational Observatory, will do both if Nature is kind enough to provide a strong enough source [2]. LIGO I is scheduled to begin data taking in 2003. The upgrade to LIGO II, with much greater sensitivity, begins in 2005. Perhaps we shall see a direct measurement of the spin of the graviton by the end of this decade.

The anomalous magnetic moment of the muon

This subject is covered in the plenary talk by G. Bunce, so I will be brief. After years of hard work and great patience, the Brookhaven experiment (E821) seems poised to report a value for $a_\mu \equiv (g_\mu - 2)/2$ which will challenge the Standard Model. It is conventional to quote values for a_μ in units of 10^{-10} or 10^{-11} and accuracy in parts per million. Thus the CERN μ^+ value is $a_\mu \times 10^{10} = 116\ 591\ 00(110)$ has an accuracy of 10 ppm [3]. The E821 number from 1998 running is $a_\mu \times 10^{10} = 116\ 591\ 91(59)$ (5 ppm), already a twofold improvement in precision over the old CERN experiment [4].

Theory includes electromagnetic, weak and strong corrections. The pure QED terms are known extremely well – they contribute $a_\mu(\text{QED}) \times 10^{11} = 116\,584\,705.7(2)$.[2] Strong (QCD) effects are very significant: one-loop hadronic vacuum polarization gives $a_\mu(\text{QCD-1 loop}) \times 10^{11} = 6924(62)$; two-loop hadronic vacuum polarization effects are important at the level of 1 ppm ($a_\mu(\text{QCD-2 loop}) \times 10^{11} = 101(6)$);[2] and QCD light-by-light scattering enters at the level just below 1 ppm ($a_\mu(\text{QCD–light-by-light}) \times 10^{11} = -85(30)$).[2] The present precision of the theoretical estimate of $(g_\mu - 2)$ is principally limited by the lack of information on QCD light-by-light scattering: $a_\mu(\text{theory}) \times 10^{11} = 116\ 591\ 62(8)$ (0.66 ppm). Until someone understands how to compute QCD light-by-light scattering more accurately, there is no point carrying experiment beyond 0.5 ppm accuracy. This limit was designed into the BNL experiment: data on tape should allow a precision of 0.5 ppm, and the experiment's ultimate goal is $\sim$0.35 ppm. At this precision a_μ is sensitive to SUSY radiative corrections from loops involving smuons and neutral and charginos, especially in models with large $\tan\beta$,

$$a_\mu(\text{SUSY}) \approx 140 \times 10^{-11} \Big(\frac{100\text{GeV}}{\tilde{m}}\Big)^2 \tan\beta \tag{1}$$

so a_μ probes SUSY masses of order 100 GeV for $\tan\beta \sim 1$. Of course, surprises beyond SUSY may await.

Electric Dipole Moments

The search for an understanding of CP-violation probably commands more resources than any other single issue in high energy physics: ε'/ε, rare K decays, B factories, etc. A classic window into CP-violation is provided by the search for electric dipole moments (EDM's). Khriplovich's PANIC99 talk gives a good summary [5]. I have abstracted Table 1 from his talk[3]. Standard Model (ie. CKM) predictions for

2) See the talk by G. Bunce for the diagrams.

3) Though the table does not do justice to the complexity of measurements of nuclear EDM's or the sophistication of Khriplovich's talk

TABLE 1. Electric Dipole Moments

Particle	Current Limit	Standard Model	Reasonable Goal
Neutron	6–10 $\times 10^{-26}$	10^{-30-31}	10^{-27-28}
Electron	4×10^{-27}	10^{-40}	10^{-28}
Nuclei	$\sim 2 \times 10^{-24}$	$\sim 10^{-30}$	—
Muon	10^{-18}	10^{-38}	10^{-24} [a]

[a] Storage ring proposal, Y. Semertzidis [6].

EDM's are far smaller than the reasonable goals of experiments. This means that EDM's provide fertile ground in which to look for sources of CP-violation *beyond* the Standard Model. Of particular interest is Semertzidis's proposal to use the BNL $(g-2)$ ring to improve the limit on the muon EDM by as much as six orders of magnitude [6]. Readers interested in this simple and elegant idea should consult the review by Khriplovich.

SPIN IN QCD

Polarization effects in QCD present a complex landscape. Asymmetries need to be explained. Sometimes we have no explanation but still can use them to probe questions or isolate effects that are perhaps even more interesting. I want to highlight some of the topics I find particularly interesting. This week's program promises many interesting talks, beyond my ability to anticipate – my apologies to all those whose work has been omitted in this brief overview.

I will focus on the overlap between theory and experiment. Many striking asymmetries occur in the low energy or nuclear domain where we have few theoretical insights into QCD [7]. A few dramatic spin-dependent effects occur in the deep inelastic domain, where QCD is transparent. Others occur where deep inelastic and soft domains overlap: the world of parton distribution and fragmentation functions. Here spin effects help elucidate the puzzling nature of hadrons and here I will concentrate.

The topics I will cover include:

- Bjorken's Sum Rule: What it means to "understand" something in QCD.
- Quark and gluon distributions in the nucleon.
- Probing polarized glue in the proton.
- The nucleon's total angular momentum: Progress and frustration.
- Transversity.
- Spin at RHIC.
- Fragmentation and spin: The new HERMES asymmetry and beyond.
- Spin dependent static moments: μ_s, the anapole, etc.
- The Drell-Hearn-Gerasimov-Hosada-Yamamoto Sum Rule

Bjorken's Sum Rule

Occasionally it is worth reminding ourselves what it means to "understand" something in QCD. In the absence of fundamental understanding we often invoke "effective descriptions" based on symmetries and low energy expansions. While they can be extremely useful, we should not forget that a thorough understanding allows us to relate phenomena at very different distance scales to one another. In Bjorken's sum rule, the operator product expansion, renormalization group invariance and isospin conservation combine to relate deep inelastic scattering at high Q^2 to the neutron's β-decay axial charge measured at very low energy. Even target mass and higher twist corrections are relatively well understood. The present state of the sum rule is

$$\begin{aligned}\int_0^1 dx\, g_1^{ep-en}(x,Q^2) = &\frac{1}{6}\frac{g_A}{g_V}\left\{1-\frac{\alpha_s(Q^2)}{\pi}-\frac{43}{12}\frac{\alpha_s^2(Q^2)}{\pi^2}-20.215\frac{\alpha_s^3(Q^2)}{\pi^3}\right\}\\ &+\frac{M^2}{Q^2}\int_0^1 x^2dx\left\{\frac{2}{9}g_1^{ep-en}(x,Q^2)+\frac{1}{6}g_2^{ep-en}(x,Q^2)\right\}\\ &-\frac{1}{Q^2}\frac{4}{27}\mathcal{F}^{u-d}(Q^2)\end{aligned} \tag{2}$$

where the three lines correspond to QCD [8], target mass, and higher twist [9] corrections respectively. g_1 and g_2 are the nucleon's longitudinal and transverse spin dependent structure functions. g_A and g_V are the neutron's β-decay axial and vector charges. $\mathcal{F}$ is a twist-4 operator matrix element with dimensions of [mass]^2, which measures a quark-gluon correlation within the nucleon,

$$\mathcal{F}^u(Q^2)S^\alpha = \tfrac{1}{2}\langle PS|\, g\bar{u}\widetilde{\mathbf{F}}^{\alpha\lambda}\gamma_\lambda u\Big|_{Q^2}|PS\rangle \tag{3}$$

where g is the QCD coupling, $\widetilde{\mathbf{F}}$ is the dual gluon field strength, and $|_{Q^2}$ denotes the operator renormalization point.

The most thorough analysis of the Bj Sum Rule I know of is one presented by SMC in 1998 [10]. Their theoretical evaluation gives

$$\int_0^1 dx\, g_1^{ep-en}(x,Q^2)|_{\text{theory}} = 0.181 \pm 0.003 \tag{4}$$

at $Q^2 = 5$ GeV^2. Experiment is not yet able to reach this level of accuracy. The latest data relevant to the Bj Sum Rule is shown in Fig. 2. The value extracted by the SMC is

$$\int_0^1 dx\, g_1^{ep-en}(x,Q^2)|_{\text{expt.}} = 0.174 \pm 0.005 \begin{array}{cc} +0.011 & +0.021 \\ -0.009 & -0.006 \end{array} \tag{5}$$

at $Q^2 = 5$ GeV^2, and the errors are statistical, systematic, and "theoretical" (eg. generated by running the data to a common Q^2), respectively [10]. Further accuracy is necessary to confirm the target mass corrections and extract the twist-four contribution.

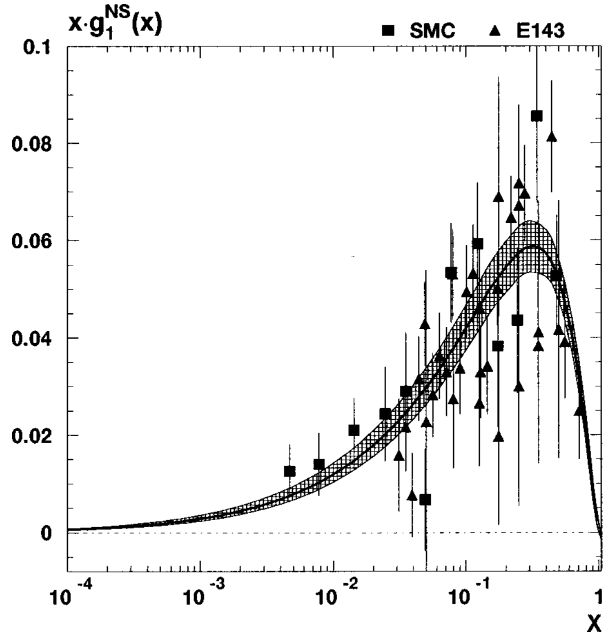

FIGURE 2. SMC analysis of data relevant to the Bjorken sum rule.

Quark and gluon distributions in the nucleon

No summary of recent progress in spin physics is complete without a survey of the polarized quark and gluon distributions in the nucleon. These helicity weighted momentum distributions are the most precise and interpretable information we have about the spin substructure of a hadron. The distributions are usually defined in terms of flavor-SU(3) structure,

$$\begin{aligned} \text{Singlet:} \quad & \Delta\Sigma = \Delta U + \Delta D + \Delta S \\ \text{Nonsinglet, isovector:} \quad & \Delta q_3 = \Delta U - \Delta D \\ \text{Nonsinglet, hypercharge:} \quad & \Delta q_8 = \Delta U + \Delta D - 2\Delta S \end{aligned} \tag{6}$$

where $\Delta Q \equiv q^{\uparrow}(x,Q^2) + \bar{q}^{\uparrow}(x,Q^2) - q^{\downarrow}(x,Q^2) - \bar{q}^{\downarrow}(x,Q^2)$. Experimenters seem to prefer nonsinglet distributions specialized to the proton and neutron individually,

$$\begin{aligned} \text{Proton nonsinglet:} \quad & \Delta q_{NS}(p) = \Delta U - \tfrac{1}{2}\Delta D - \tfrac{1}{2}\Delta S \\ \text{Neutron nonsinglet:} \quad & \Delta q_{NS}(n) = \Delta D - \tfrac{1}{2}\Delta U - \tfrac{1}{2}\Delta S \end{aligned} \tag{7}$$

so that

$$\begin{aligned} g_1^p &= \tfrac{2}{9}\Delta\Sigma + \tfrac{2}{9}\Delta q_{NS}(p) \\ g_1^n &= \tfrac{2}{9}\Delta\Sigma + \tfrac{2}{9}\Delta q_{NS}(n). \end{aligned} \tag{8}$$

Since the integrated quark spin accounts for only about 30% of the nulceon's spin, it is extremely interesting to know whether the integrated gluon spin in the nucleon is large. Of course the polarized gluon distribution, $\Delta g(x,Q^2)$, cannot be measured directly in deep inelastic scattering because gluons do not couple to the electromagnetic

current. Instead Δg is inferred from the QCD evolution of the quark distributions. [See Ref. [10] for details of the process and references to the original literature.] However, evolution of imprecise data only constrains a few low moments of Δg and gives only crude information on global characteristics such as the existence and number of nodes. It is clear that Δg must be measured directly elsewhere.

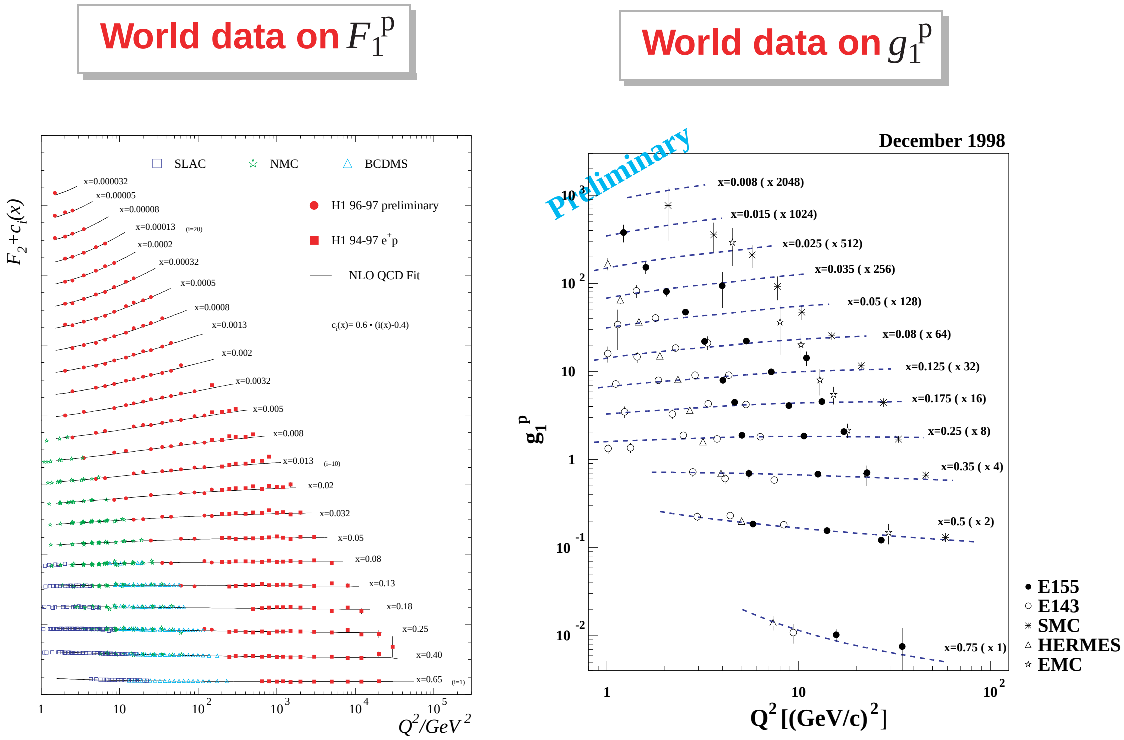

FIGURE 3. World data on spin-average and spin-dependent structure functions [11].

That said, the world's data on polarized structure functions is summarized in Figs. 3 and 4. Fig. 3 is taken from Naomi Makins's talk at DIS2000 and presents the world's data on g_1^p in the same format traditionally used for unpolarized structure function data [11]. The figure highlights the tremendous progress of the past decade as well as the need for much better data if our knowledge of polarized distributions would aspire to the same accuracy as unpolarized distributions. Fig. 4 shows the quark and gluon distributions extracted from the world's data by SMC, together with estimates of systematic and theoretical uncertainties [10]. While the information on quark distributions is fairly precise, it is clear that we know very little about the distribution of polarized gluons in the nucleon.

Probing polarized glue in the nucleon

As must have been clear from the preceeding discussion, a direct measurement of the polarized gluon distribution in the nucleon is probably the highest priority for groups interested in QCD spin physics. Further refinement of the indirect method

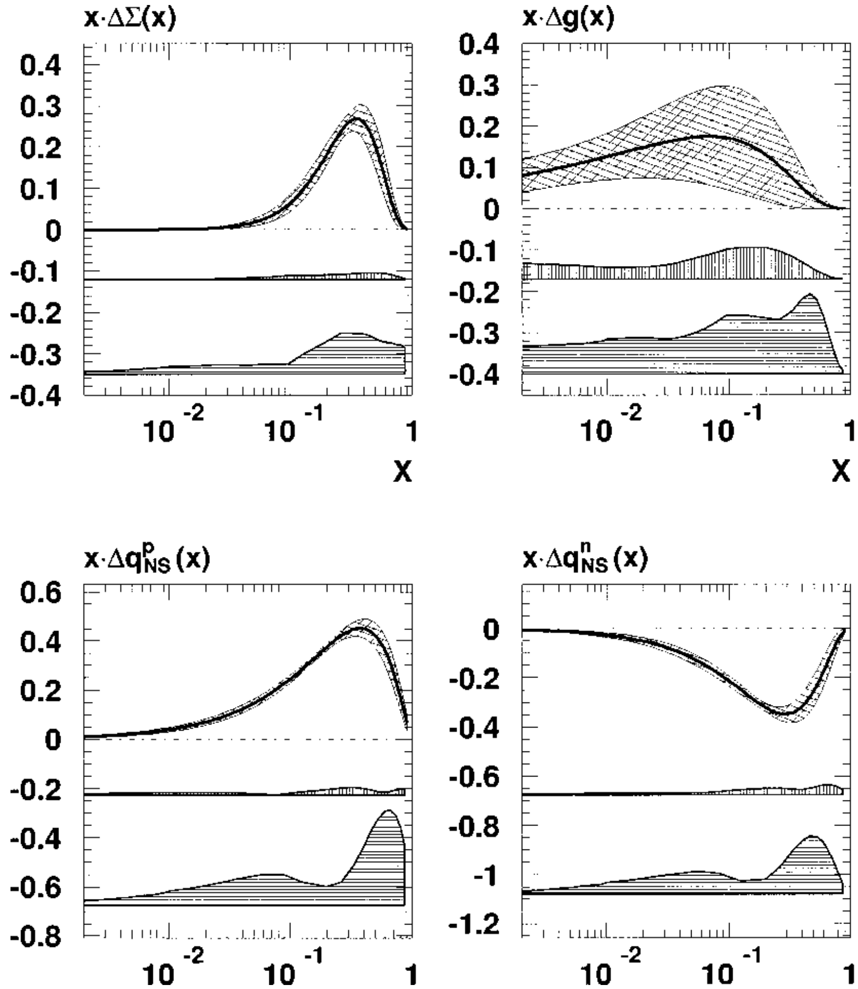

FIGURE 4. Polarized quark and gluon distribution functions. The upper figures show the distribution with a statistical error bound. The lower figures show estimates of systematic and theoretical uncertainties, respectively.

championed by SMC will contribute to this goal, but direct measurement is essential.

Several direct methods are being pursued:

- $\bar{c}c$ pair production in $e\vec{p}_{\|} \rightarrow e'\bar{c}cX$ and related methods.

  The COMPASS Collaboration has proposed to extend this powerful probe of the unpolarized gluon distribution to the polarized case [12]. The basic mechanism is photon-gluon fusion, as shown in Fig. 5. For further discussion see the talk by Bradamante at this meeting.

  Variations on this method include two jet production: $e\vec{p}_{\|} \rightarrow e'$ jet jet X at large transverse momentum (as originally envisioned by Carlitz, Collins, and Mueller [13]); $\bar{c}c$ photoproduction $\gamma\vec{p}_{\|} \rightarrow \bar{c}cX$; and pion pair production, $\gamma\vec{p}_{\|} \rightarrow \pi\pi X$, which Hermes hopes to use a lower center of mass energies where $\bar{c}c$ and two jet production are not available [14].

- Single photon production at high transverse momentum in polarized $\vec{p}_{\|}\vec{p}_{\|} \rightarrow$

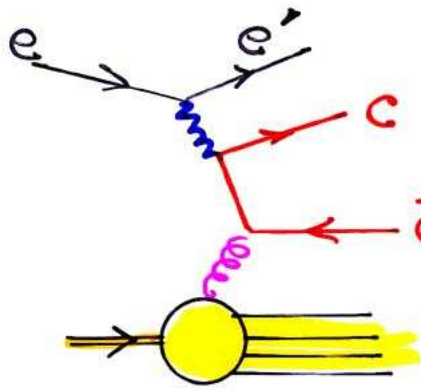

FIGURE 5. Measuring the polarized gluon distribution in $e\vec{p}_{\|} \to e' c\bar{c}X$.

γ jet X and related methods.

This is a prime goal for the polarized proton program at RHIC [15]. Here the basic mechanism is the QCD Compton process as shown in Fig. 6. This process should be an excellent probe of the polarized gluon distribution. However there is some controversy about higher-order QCD corrections that has yet to be resolved in the unpolarized case. Variations replace the high energy photon with a jet, or in the case of poor jet acceptance, a leading pion at high transverse momentum.

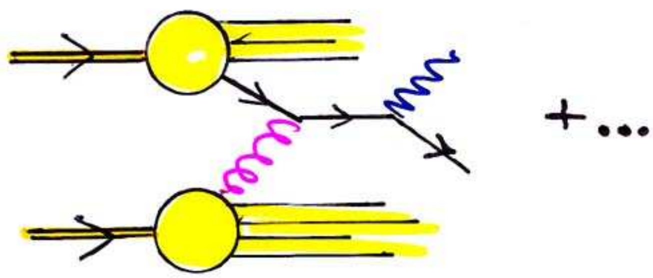

FIGURE 6. Measuring the polarized gluon distribution in $\vec{p}_{\|}\vec{p}_{\|} \to \gamma$ jet X.

Estimates of the precision of these methods have become available as better simulations come on line for COMPASS and RHIC. The projections for $\vec{p}_{\|}\vec{p}_{\|} \to \gamma$ jet X are shown in Fig. 7. An estimate of the COMPASS sensitivity is shown in Fig. 8. In both cases the experiments are compared with gluon distributions proposed by Gehrmann and Sterling. Clearly, the polarized proton program at RHIC has a major contribution to make in this area.

The nucleon's total angular momentum

In the old days (pre-1988), it was clear that quark and gluon spin distributions could be measured in deep inelastic scattering. In some uncertain sense they were imagined to be part of a relation that gave the nucleon's helicity,

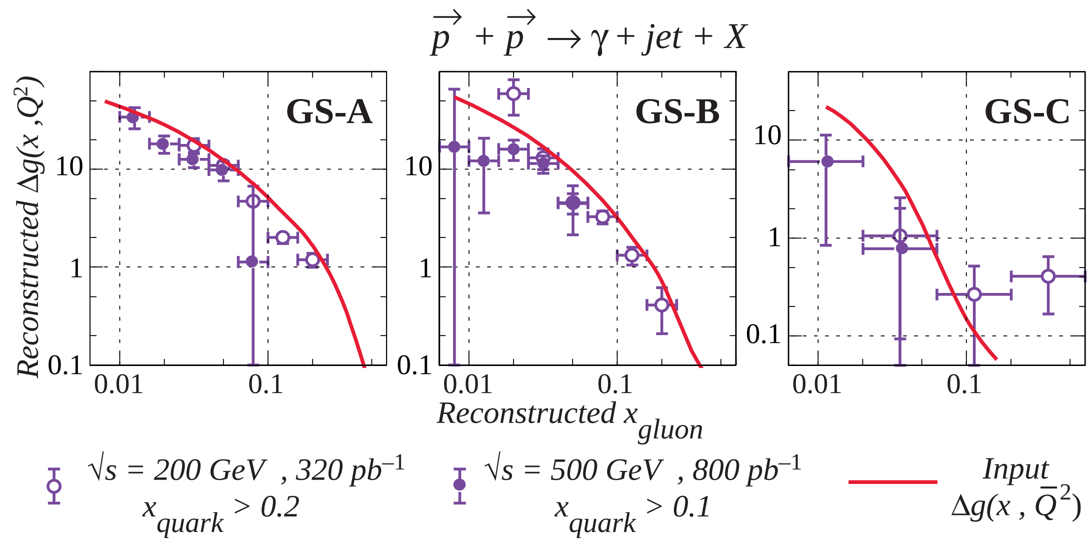

FIGURE 7. Estimates of polarized gluon distribution functions from $\vec{p}_{\|}\vec{p}_{\|} \rightarrow \gamma$ jet X at RHIC.

$$\tfrac{1}{2} = \tfrac{1}{2}\Delta\Sigma + \Delta g + \text{the rest} \tag{9}$$

where "the rest" was not well understood. $\Delta\Sigma$ and Δg were (and are) measurable, gauge invariant, and given by integrals over x, $\Delta\Sigma = \Delta\Sigma(Q^2) = \int_0^1 dx \Delta\Sigma(x, Q^2)$, $\Delta g = \Delta g(Q^2) = \int_0^1 dx \Delta g(x, Q^2)$.

Significant progress occured in the late 80s and 90s as the other pieces of the angular momentum were related to local, gauge invariant operators [16]. This line of work culminated in Ji's decomposition of the nucleon's helicity [17],

$$= \tfrac{1}{2}\Delta\Sigma + \hat{L}_q + \hat{J}_g \tag{10}$$

where $\hat{L}_q$ is the nucleon matrix element of an operator that rotates quarks' orbital motion about the $\hat{e}_3$-axis in the rest frame. It is one candidate for a definition of the quark orbital angular momentum in the nucleon. $\hat{J}_g$ is the nucleon matrix element of the operator that rotates the gluon about the $\hat{e}_3$ axis. Ji showed that $\hat{J}_g$ cannot be further decomposed into Δg and an orbital contribution given by a local gauge invariant operator. This should not be too surprising because it is well known that Δg itself cannot be expressed in terms of a *local* gauge invariant operator [18]. [In general the operator is non-local, but becomes local in $A^+ = 0$ gauge.] The virtue of eq. 10 is that $\hat{L}_q$ can be measured in deeply virtual Compton scattering (DVCS). Although $\hat{J}_g$ is in principle also measurable in DVCS, it requires a precision study of Q^2 *evolution* and is impossible in practice.

Most recently it has been possible to define gauge invariant *parton distributions* for all the components of the nucleon's angular momentum [19–21],

$$\tfrac{1}{2} = \int_0^1 dx \left\{ \tfrac{1}{2}\Delta\Sigma(x, Q^2) + \Delta g(x, Q^2) + L_q(x, Q^2) + L_g(x, Q^2) \right\} \tag{11}$$

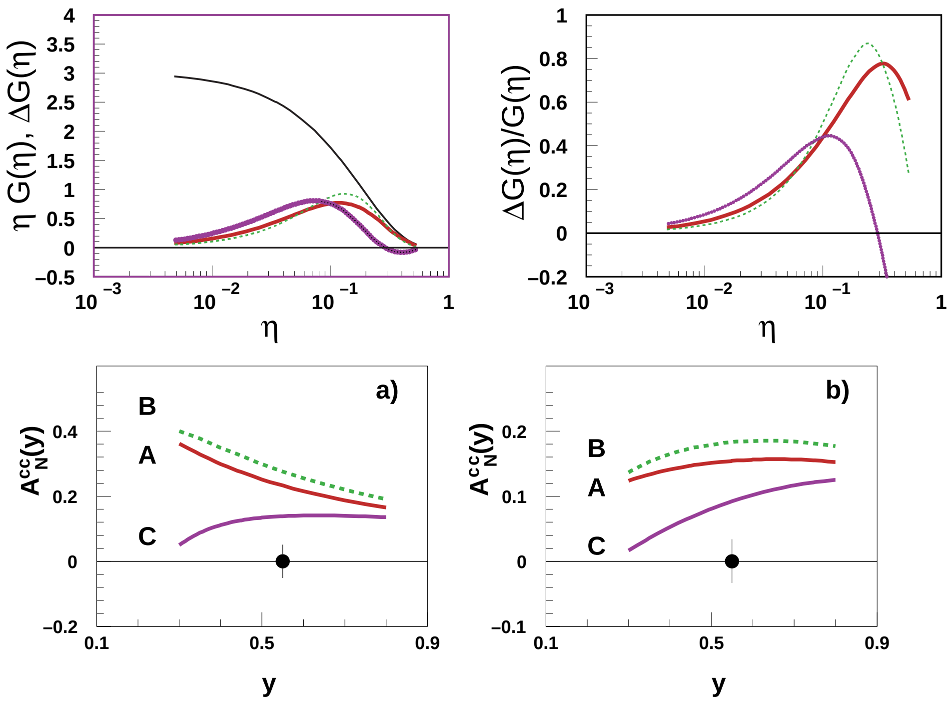

FIGURE 8. Gluon-associated assymetries for $\gamma\vec{p}_{\|} \rightarrow e'c\bar{c}X$ at COMPASS. See Bradamante's talk for details.

where L_q and L_g are Bjorken-x distributions of quark and gluon *orbital* angular momentum in the infinite momentum frame. L_q and L_g are given by the light-cone fourier transforms of bilocal operator products just like other parton distributions. This decomposition has many virtues: the four terms evolve into one another with Q^2 [19,20], each term is the Noether charge associated with the appropriate transformation of quarks or gluons [21]. Thus $L_g(x, Q^2)$ is the observable associated with the orbital rotation of gluons with momentum fraction x, about the infinite momentum axis in an infinite momentum frame. On the other hand, eq. 11 suffers from a significant drawback: unlike Ji's $\hat{L}_q$, we know of no way to measure either $L_q(x, Q^2)$ or $L_g(x, Q^2)$. They do not appear in the description of DVCS.

So the situation with respect to a complete description of the nucleon's angular momentum is frustrating. The theory is under control. Eq. 11 summarizes all we would like to know, but we do not know how to measure what we would like to know.

Transversity

One of the major accomplishments of the recent renaissance in QCD spin physics has been the rediscovery and exploration of the quark *transversity distribution*. First mentioned by Ralston and Soper in 1979 in their treatment of Drell-Yan μ-pair production by transversely polarized protons [22], the transversity was not recognized as a major component in the description of the nucleon's spin until the early 1990's [23–26]. We now know that the transversity, $\delta q(x, Q^2)$, together with the unpolarized distribution, $q(x, Q^2)$, and the helicity distribution, $\Delta q(x, Q^2)$, are required to give a complete

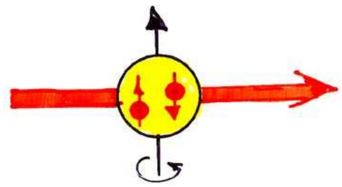

FIGURE 9. Transversity: transversely polarized quarks in a nucleon at infinite momentum.

description of the quark spin in the nucleon at leading twist. An equation tells this story clearly –

$$\mathcal{A}(x,Q^2) = \tfrac{1}{2}q(x,Q^2)\ I\otimes I + \tfrac{1}{2}\Delta q(x,Q^2)\ \sigma_3\otimes\sigma_3 \\ + \tfrac{1}{2}\delta q(x,Q^2)\ \ (\sigma_+\otimes\sigma_- + \sigma_-\otimes\sigma_+) \qquad (12)$$

Here, $\mathcal{A}$ is the quark distribution in a nucleon as a density matrix in both the quark and nucleon helicities (hence the external product of two Pauli matrices in each term). q governs spin average physics, Δq governs helicity dependence, and δq governs helicity flip – or transverse polarization – physics.

The transversity can be interpreted in parton language as the probability to find quarks of momentum fraction x, transversely polarized in a transversely polarized nucleon at infinite momentum. This is illustrated in Fig. 9.

The quark momentum distribution is well known and the helicity distribution is becoming better known. In contrast nothing is known about transversity from experiment. This is because it decouples from inclusive DIS. At leading twist helicity and chirality are identical. Transversity corresponds to helicity (and therefore chirality) flip. So transversity decouples from processes with only vector or axial vector couplings. This is shown schematically in Fig. 10a. In order to access transversity it is necessary to flip a quark's helicity in one soft process and compensate with another soft helicity flip process. Two examples where transversity does not decouple are transverse Drell-Yan: $\vec{p}_\perp\vec{p}_\perp \to \mu^+\mu^- X$ (the original Ralston-Soper process where transversity was discovered) and semi-inclusive DIS where a final state fragmentation function flips helicity: $e\vec{p}_\perp \to e'\vec{h}_\perp X$, of which several examples exist. Both are shown schematically in Fig. 10b and c.

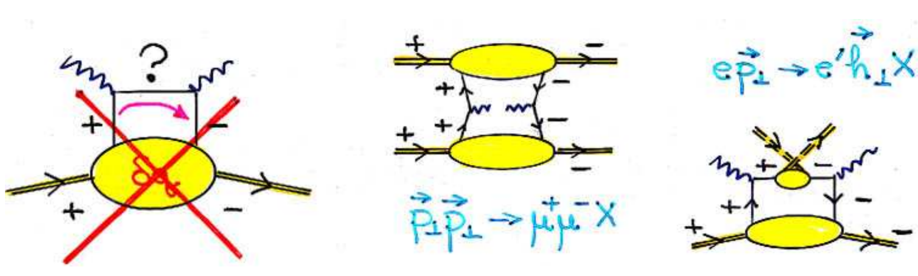

FIGURE 10. Deep inelastic processes relevant to transversity.

Measurements of quark transversity rank high on the agendas of Hermes, COMPASS and RHIC. Interest in this possibility has been piqued by the azimuthal pion asymmetry recently reported by Hermes, as will be discussed below.

Spin commissioning at RHIC

One of the most important landmarks of the past year was the successful spin commissioning run just concluded at RHIC. N. Saito will report in detail in his plenary talk. Polarized protons were accelerated in the AGS, and injected and stored in RHIC. The Coulomb-nuclear interference polarimeter functioned as expected. The Siberian snake in RHIC rotated the polarization as planned. Polarized beam was accelerated in RHIC past depolarizing resonances and the polarization was preserved with the aid of the snake. These milestones mark the beginnings of polarized collider physics at RHIC, and a whole new window on the deep spin structure of hadrons. This new facility would not have been possible without the support of RIKEN and the effort of a team of Japanese experimenters working at BNL and supported by the joint RIKEN/BNL Research Center. Working with both major RHIC detector groups, STAR and PHENIX, the RHIC Spin Collaboration has developed an ambitious program for probing spin structure in QCD.

Fragmentation and spin: The Hermes asymmetry and beyond

To my mind the single most interesting development in QCD spin physics reported since SPIN98 is the azimuthal asymmetry in pion electroproduction from Hermes [27]. It is interesting in itself and also as an emblem of a new class of spin measurements involving spin-dependent fragmentation processes, which act as filters for exotic parton distribution functions like transversity.

Fragmentation functions allow us to access and explore the spin structure of unstable hadrons, which cannot be used as targets for deep inelastic scattering. Examples include the longitudinal and transverse spin dependent fragmentation functions of the Λ, schematically $\vec{q}_{\|} \to \vec{\Lambda}_{\|}$ and $\vec{q}_{\perp} \to \vec{\Lambda}_{\perp}$. Since the $\Lambda \to p\pi$ decay is self-analysing it is relatively easy to measure the spin of the Λ. By selecting Λ's produced in the current fragmentation region one can hope to isolate the fragmentation process $q \to \Lambda$. The principal challenge of such measurements is for theorists: we have no theoretical framework for analysing fragmentation functions. Having measured the quark spin structure of the nucleon, we can use flavor-SU(3) to estimate the way quark spins are distributed in the Λ [28]. However we do not know if this information is reflected in the fragmentation process $q \to \Lambda$. Another, perhaps less obvious, example is the tensor fragmentation function of the ρ, denoted schematically by $(q \to \rho_{\pm}) - (q \to \rho_0)$, where ρ_h are ρ helicity states [29]. ρ decay transmits no spin information, but it distinguishes the longitudinal and transverse helicity states required for this measurement. The data are already available. The challenge to theorists is to make use of it.

Even if we do not know how to interpret fragmentation functions, we can use them as filters, to select parton distribution functions that decouple from completely inclusive DIS. The salient example is the use of a helicity flip fragmentation function to select the quark transversity distribution. As shown in Fig. 10c, by interposing a helicity flip fragmentation function on the struck quark line in DIS, it is possible

to access the transversity. There are several candidates for the necessary helicity flip fragmentation function:

- $e\vec{p}_\perp \to e'\vec{\Lambda}_\perp X$

  In this case the helicity flip fragmentation function of the Λ is exactly analogous to the transversity distribution function in the nucleon [30,31]. The only difficulty with this example is the relative rarity of Λ's in the current fragmentation region, and the possibly weak correlation between the Λ polarization and the polarization of the u quarks, which dominate the proton.

- $e\vec{p}_\perp \to e'\pi(\vec{k}_\perp)X$ [32]

  [The "Collins Effect"] In this case the azimuthal angular distribution of the pion relative to the $\vec{q}$ axis can be analyzed to select the interference between pion orbital angular momentum zero and one that correlates with quark helicity flip. In more traditional terms the effect is proportional $\vec{S}_\perp \cdot \vec{q} \times \vec{p}_\pi$. This is multiplied by the quark transversity in the target and an unknown fragmentation function (known as the Collin's function) describing the propensity of the quark to fragment into a pion in a superposition of orbital angular momentum zero and one states. The fact that fragmentation functions depend on z while distribution functions depend on x allows the shape of the transversity distribution to be measured in this manner.

- $e\vec{p}_\perp \to e'\pi\pi X$ [33,34]

  In this case the angular distribution of the two pion final state substitutes for the azimuthal asymmetry.

Last year Hermes announced the observation of an azimuthal asymmetry similar to the Collin's asymmetry described above, but with a longitudinally polarized target: $e\vec{p}_\parallel \to e'\pi(\vec{k}_\perp)X$. Their data are shown in Fig. 11. This asymmetry could be a (suppressed) reflection of the Collins effect because the target spin, while parallel to the electron beam, has a small component, $\mathcal{O}(1/Q)$ perpendicular to the virtual photon. It could also result from competing twist-three helicity flip effects also suppressed by $1/Q$. Unless the Hermes asymmetry is entirely twist three, which seems unlikely, it appears that the prospects for observing a large azimuthal asymmetry from a *transversely* polarized target are very good. Hermes will be running with a transversely polarized target this year and their results will be awaited with considerable excitement.

Spin-dependent static moments

Polarization effects abound in the strong interactions at low energies. Some are quite striking, but most defy theoretical analysis because they occur in two body scattering (or more complex processes), which we do not know how to analyse in QCD. One striking exception, quite similar in many ways to deep inelastic physics, are the spin (and flavor) dependent static moments of the nucleon. In general these are measured in elastic lepton nucleon scattering, $\ell N \to \ell' N$. The general form is

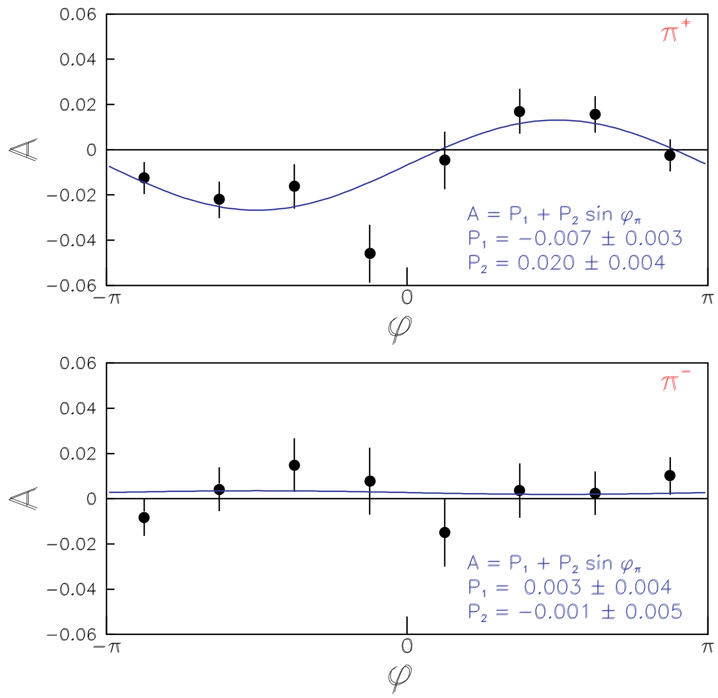

FIGURE 11. The Hermes azimuthal asymmetry.

$$\Gamma \propto \langle PS|\bar{q}\Gamma q|PS\rangle \tag{13}$$

where Γ is some operator in the spin and/or space coordinates of the quark field. Familiar examples include the axial charges ($\Gamma = \gamma_\mu\gamma_5$), magnetic moments ($\Gamma = \frac{1}{2}\vec{r}\times\vec{\gamma}$), and charge radii ($\Gamma = (\vec{r})^2$). A less familiar example is the "tensor charge" ($\Gamma = \sigma^{0i}\gamma_5$), which though measurable in principle, does not couple to any electroweak current and cannot be measured in $\ell N \to \ell' N$. The isovector, $u-d$, and hypercharge, $u+d-2s$, flavor combinations are relatively easy to measure given the variety of electroweak currents and baryons related to one another by flavor-SU(3) transformations. However, the third flavor combination, $u+d+s$, does not appear in the electromagnetic or charge-changing weak currents, and cannot be constructed by flavor-SU(3) rotations because it is a flavor-SU(3) singlet and all the other currents are flavor-SU(3) octets.

Much progress has been made in recent years both by theorists, who have learned that the nucleon's tensor charge is related to the lowest moment of its transversity structure function (in analogy to the Bjorken Sum Rule); and by experimenters, who have measured the flavor combination $u+d+s$ (and therefore the strangeness matrix elements) by extracting the Z^0-nucleon coupling via parity violating ep elastic scattering. The Z^0 couples to weak isospin (hence $u-d+s-c\ldots$) that, restricted to light quarks, is a linear combination including the flavor singlet. Table 2 shows a simplified summary of the Dirac and flavor structure of some static matrix elements and how they are measured.

Two flagship measurements in this area are the extraction of μ_s, the nucleon matrix element of $s^\dagger\frac{1}{2}\vec{r}\times\vec{\gamma}s$, from parity violating $ep \to ep'$ (the SAMPLE experiment at Bates), and extraction of $\langle r_s^2\rangle$, the nucleon matrix element of $s^\dagger(\vec{r})^2 s$, from the same process in a different kinematic domain (the HAPPEX experiment at JLab). Of

TABLE 2. Electric Dipole Moments

Flavor	$\vec{\gamma}\gamma_5$	Dirac Structure $\vec{r}\times\vec{\gamma}$	$\sigma^{0i}\gamma_5$
$u-d$	β-decay	Nucleon mag. mom.	Transverse DIS
$u+d-2s$	Hyperon β-decay	Hyperon mag. mom.	Transverse DIS
$u+d+s$	Polarized DIS	Parity odd $\vec{c}p \to ep$	Transverse DIS
	$q+\bar{q}$	$q-\bar{q}$	$q-\bar{q}$

course the latter is not really spin-physics, but it belongs in the same discussion. HAPPEX first run at relatively large momentum transfer saw no sign of a nucleon strange electric form factor [35]. No statement can be made about $\langle r_s^2 \rangle$, however, until data at lower Q^2 become available.

SAMPLE's initial results are quite interesting – for unexpected reasons [36]. The signal of interest, the Z^0-nucleon coupling, is contaminated by a parity violating photon-nucleon interaction, the so called "anapole moment", and by higher-order weak radiative corrections to electron nucleon scattering (see Fig. 12). The anapole and weak radiative corrections are not known a priori and have to be estimated in models [37,38]. They are parameterized by $G_A^e(T=1)$ in Fig. 13. A single measure-

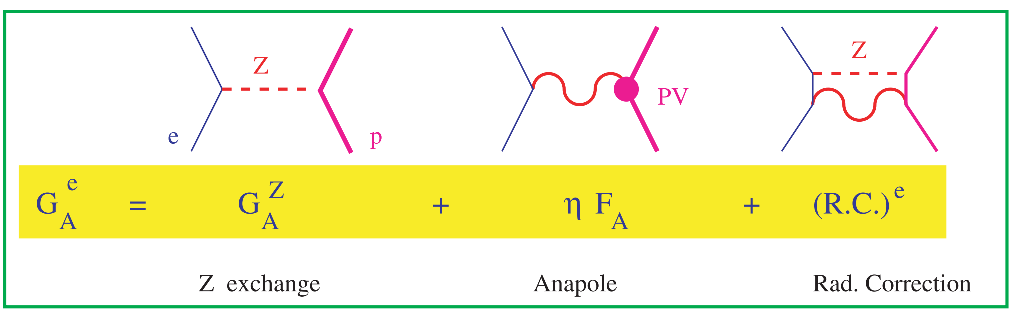

FIGURE 12. Contributions to parity violation in $ep \to ep'$.

ment, say $\not{\Pi}$ $ep \to ep$, gives a line in the $G_M^s - G_A^a(T=1)$ plane. The initial SAMPLE measurement together with the Holstein-Ramsey-Musolf estimate of $G_A^a(T=1)$ gave a large positive estimate for $\mu_s(p)$ (admittedly with large error bars) in contrast to model calculations that typically give negative μ_s [36]. Most recently, SAMPLE has announced measurements off a deuteron target, $\not{\Pi}$ $ed \to ed$, which give an independent line in the $G_M^s - G_A^a(T=1)$ plane [39]. The result, shown in Fig. 13b, suggests the estimate of $G_A^a(T=1)$ may be wrong and that μ_s is closer to zero, though certainly compatible with theoretical models predicting small negative values.

These are only the earliest results in what promises to be a productive study of the strangeness content of the nucleon using very precise measurements of parity violating elastic lepton nucleon scattering.

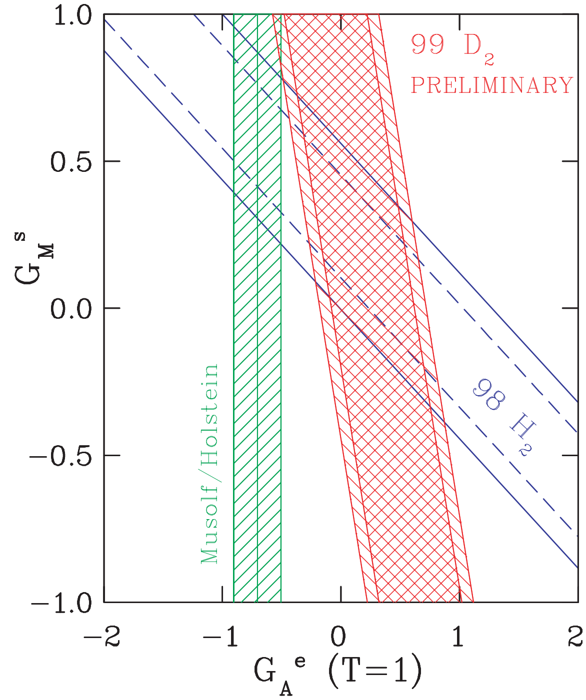

FIGURE 13. Interpretation of SAMPLE measurements.

The Drell-Hearn-Gerasimov-Hosada-Yamamoto Sum Rule

The prospects for a definitive test of this deep and ancient sum rule [40–42] are now excellent. Experiments proposed and/or underway at Mainz and JLab will cover a wide range of energies with high polarization and high statistics. The question I would like to address here is "What does the DHGHY sum rule test?". The sum rule reads,

$$\frac{2\pi^2\alpha}{M^2}\kappa^2 = \int_0^\infty \frac{d\nu}{\nu}\left(\sigma_P(\nu) - \sigma_A(\nu)\right) \tag{14}$$

where κ and M are the anomalous magnetic moment and mass of the target, and $\sigma_{P,A}$ are the total photoabsorption cross sections (as functions of the laboratory photon energy, ν) for target and photon spins parallel and antiparallel.

The sum rule rests on two assumptions:

- Low's low-energy theorem

  Many years ago Low derived an extension of the Thompson limit in Compton scattering [43]. The nucleon's forward Compton amplitude can be written

  $$f(\nu) = f_1(\nu^2)\vec{\varepsilon}'^{*}\cdot\vec{\varepsilon} + \nu f_2(\nu^2) i\vec{\sigma}\cdot\vec{\varepsilon}'^{*}\times\vec{\varepsilon} \tag{15}$$

  where f_1 and f_2 are the spin-nonflip and spin-flip amplitudes respectively.

  Using gauge invariance and QED, Low showed

  $$f_2(0) = -\tfrac{1}{2}\frac{\alpha}{M^2}\kappa^2\ . \tag{16}$$

- An unsubtracted dispersion relation

  Analyticity, crossing and unitarity dictate that the forward Compton amplitudes satisfies dispersion relations, which combine Cauchy's theorem with the optical theorem ($\mathrm{Im} f(\nu) \propto \sigma(\nu)$),

$$\mathrm{Re} f_2(\nu) = \sum_{j=0}^{J_{MAX}} c_j \nu^{2j} + \frac{1}{8\pi^2} \mathrm{P} \int_0^\infty d\nu'^2 \frac{\sigma_A(\nu') - \sigma_P(\nu')}{\nu'^2 - \nu^2} \tag{17}$$

  The polynomial is usually omitted in writing the dispersion relation, however it is not excluded by analyticity or unitarity. Since it has no imaginary part, it does not affect the measurable cross sections. For the moment let us omit the polynomial.

Then the DHGHY sum rule is obtained by evaluating $f_2(0)$ with the aid of the dispersion relation, and equating it to Low's low energy limit.

What could go wrong with this? Absent any problems with electrodynamics, the only weak point is ignoring the possible polynomial in the dispersion relation. Since we need only $f_2(0)$ only the constant term (c_0) in the polynomial matters. Usually, limits on the growth of amplitudes at high energies are invoked to restrict the order of the polynomial. However, they do not exclude the constant, c_0. In the standard derivations c_0 is simply ignored. This is called the assumption of an "unsubtracted dispersion relation". This is something of a misnomer: If the integral eq. 17 diverged it would be *necessary* to reformulate it by formally subtracting $f_2(0)$ (remember we are assuming $c_1 = 0, c_2 = 0, \ldots$). The resulting integral would be more convergent, but now the constant $f_2(0)$ would appear in the relation,

$$\mathrm{Re} f_2(\nu) = \mathrm{Re} f_2(0) + \frac{\nu^2}{8\pi^2} \mathrm{P} \int_0^\infty d\nu'^2 \frac{\sigma_A(\nu') - \sigma_P(\nu')}{\nu'^2(\nu'^2 - \nu^2)} \tag{18}$$

This is a "subtracted dispersion relation". Now substitution into the Low's theorem yields nothing useful. Even if the dispersion relation does not *need* subtraction, ie. even if the integral in eq. 17 converges, still the constant c_0 could be non-zero and spoil the sum rule. Therefore, measurement of the high-energy behavior of σ_A and σ_P *does not* determine whether an additive constant is present in the dispersion relation.

Debate about the validity of the DHGHY sum rule usually centers on whether the dispersion integral needs subtraction. Even if it doesn't, the sum rule could be ruined by a non-zero, real constant in $f_2(\nu)$. Such a constant is called, for historical reasons, a "$J = 0$ fixed pole". So the question of the validity of the DHGHY sum rule comes down to whether $J = 0$ fixed poles occur in QCD. It is known that they do not occur in low orders of perturbation theory. This was first verified when the electroweak anomalous magnetic moment of the muon was first calculated using a generalization of these methods [44]. It has been subsequently studied to higher orders. Brodsky and Primack have argued that it does not occur in ordinary bound states [45] – that the anomalous magnetic moment of hydrogen can be calculated from a generalized DHGHY sum rule with out a $J = 0$ fixed pole. Still, the verdict is out in QCD, where bound states are not so simple.

If the DHGHY sum rule is verified experimentally this question will recede to a footnote to history. If, however, experiment fails to confirm it, we will all have a lot to learn about $J = 0$ fixed poles!

CONCLUSIONS

My conclusions are brief. We have made striking progress in recent years. The prospects for further progress are excellent. I expect that spin physics will continue to surprise us as it has in the past. The reason is that spin is fundamentally quantum mechanical in its origins so that it beggars our classical intuition. Remember – we don't even know why matter ≡ fermions exists!

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